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NONLINEAR SOIL-PILE INTERACTION UNDER VERTICAL AND COUPLED MOTION

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ABSTRACT

This paper presents the test results of single ($L/d = 15$) and 2×2 group piles ($L/d = 15$ and $s/d = 2, 3, 4$) subjected to strong vertical and coupled vibration. The observed response curves display marked nonlinearity as the natural frequencies decrease with increasing intensity of excitation. The measured response is compared with the results obtained by using the continuum approach of Novak with dynamic interaction factor. To account for the nonlinear response of the piles, provisions are made for yielding of soil around the piles by introducing the weak boundary zone concept in the model. Different separation lengths between the pile and top soil are considered for different excitation intensities in the nonlinear analysis. Comparison with the test results show that the accuracy of the nonlinear analysis in predicting the dynamic response depends on the choice of parameters that best characterize the response of boundary zone around the pile and the realistic length of pile separation. The test data are used to establish the empirical relationships between the extent of soil separation around the pile and the maximum amplitudes for both vertical and coupled vibration. It is also found that the pile-soil-pile interaction and the embedded effect of the pile cap play a major role in the dynamic response of pile foundation.

INTRODUCTION

The interaction between pile foundation and the surrounding soil represents one of the least understood topics of foundation dynamics. A further complication in this dynamic response comes from the interaction between each of the piles in a pile group. If the spacing between the piles is very wide, the group stiffness can be evaluated simply by summing the contributions from the single piles. Piles that are closely spaced will have a significant effect on one another during dynamic loading. As a result, the group efficiency under dynamic excitation exhibits a strong oscillatory behaviour.

Different approaches have been developed to analyze the single and group pile under dynamic load in both uniform and layered soil medium. In the early development, the soil-pile system was idealized as a massless equivalent cantilever (Prakash and Agarwal, 1965) with single concentrated mass at the top and its resonant frequency was determined by using Rayleigh's method. Nogami *et al.* (1992) and Pender and Pranjoto (1996) used Winkler foundation model to evaluate the dynamic response of single pile allowing for nonlinear soil behavior. Subsequently Novak (1974) and Novak and Aboul-Ella (1978) have attempted to eliminate some of the limitations of the discrete spring and dashpot models by

considering approximate wave propagation along horizontal layers and also at the pile tip by using elastic continuum type formulation. Novak and Sheta (1980) accounted the nonlinear behaviour of soil around the pile in linear viscoelastic medium by introducing a weak cylindrical zone with reduced shear modulus. Veletsos and Dotson (1986) and Novak and Han (1990) subsequently accounted the inertia effect for the weak zone analysis.

The available literature on test results with piles and pile groups subjected to dynamic loading is very limited due to the difficulties in conducting such dynamic tests on pile foundation. Dynamic tests have been performed previously on small-scale piles by Novak and Grigg (1976) and El Sharnouby and Novak (1984). Full scale dynamic tests on pile were conducted in the field by some researchers (Vaziri and Han 1991). So there is a need to provide an experimental database on a large number of piles undergoing different modes of vibration.

In this paper, a comprehensive study involving both dynamic testing of pile foundation and theoretical analysis is presented. The dynamic tests were carried out for both vertical and

coupled motion on small prototype reinforced concrete single pile and 2×2 group piles. Frequency versus amplitude curves of piles were experimentally established in the field for different excitation intensities. The test results are compared with the results obtained by continuum approach of Novak with nonlinear solutions. The influences of various boundary zone parameters and pile-soil separation on the dynamic response of piles are also studied.

EXPERIMENTAL INVESTIGATION

The site was located adjacent to Hangar, at Indian Institute of Technology, Kharagpur Campus, India. The soil properties were determined by in-situ and laboratory tests. Two different in situ tests were conducted, namely, standard penetration tests (SPT) to determine N value and cross hole seismic tests for determining the shear wave velocity (or shear modulus) of soil layer. Tests were conducted on 0.1 m diameter (d) and 1.5 m long (L) R.C.C. piles. The piles were constructed in the field by bored cast-in-situ method. In this study, one single pile and 2×2 group piles of three different spacing ($s = 2d, 3d, 4d$) were used for the investigation. The dimension of pile cap was 0.57 m x 0.57 m x 0.25 m.

Forced vibration tests were conducted on model single piles and pile groups for different modes of vibration. A Lazan type mechanical oscillator with two counter rotating eccentric masses was used to produce the harmonic excitation force that is proportional to the square of the excitation frequency. The excitation force is given by

$$P(t) = m \cdot e \cdot \omega^2 \sin \omega t = \frac{W}{g} \cdot e \cdot \omega^2 \sin \omega t \quad (1)$$

Where m is the eccentric mass, W is the eccentric weight, e is the eccentric distance of the masses, t is the time, and g is the gravitational acceleration. The magnitude of the exciting force was changed by adjusting the angle of the eccentric mass. In order to connect the pile cap to the loading system, four foundation bolts were attached on the pile cap. For vertical vibration tests the mechanical oscillator was mounted at the centre of the pile cap in such a way so that the two rotating mass were placed horizontally and thus it produced vertical vibration. For coupled vibration tests, the mechanical oscillator was connected at the centre of the pile cap and the rotating mass of the mechanical oscillator were placed vertically. In this arrangement, both horizontal vibration and rocking vibration were generated simultaneously by the mechanical oscillator. The mass of the system was controlled using steel ingots or test bodies which were attached to the pile cap. The test body was comprised of steel ingots each weighing 650 N (8 numbers) and 450 N (10 numbers).

Whole set up was connected so that it acts as a single unit. The mechanical oscillator was connected by means of a flexible shaft with a DC motor and its speed was controlled by a speed

control unit. The vibration measuring equipment consisted of two piezoelectric acceleration pickups and the associated vibration meter. For vertical vibration measurements, each pickup was mounted vertically at equidistant positions from the foundation center on the two axis of symmetry. The complete setup of vertical vibration test on piles is shown in Figure 1. For coupled vibration measurement, the horizontal component was measured using one pickup connected to the side of the foundation at the level of center of gravity (C.G.), while the rocking amplitudes were measured simultaneously by another pickup mounted vertically on the axis of the pile cap. The arrangement of test bodies, oscillator and vibration pickups are shown in Figure 2.

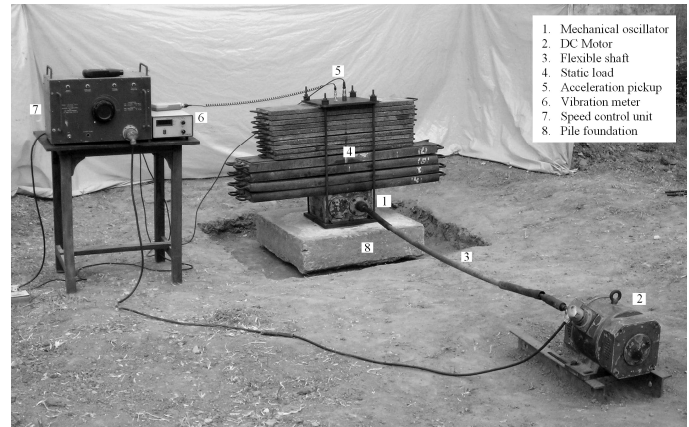


Fig. 1. Complete view of vertical vibration test setup

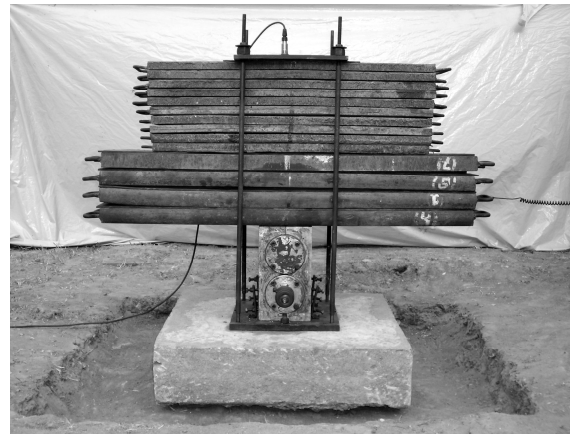


Fig. 2. Arrangements of pile cap, oscillator and test bodies for coupled vibration test

The oscillator was then run slowly through a motor using speed control unit to avoid sudden application of high magnitude dynamic load. Frequency and the corresponding amplitude of vibration was recorded by photo tachometer and vibration meter, respectively for different excitation intensities. Finally, frequencies versus displacement amplitude curves were plotted.

Tests were carried out for two different embedded depths (h) of pile cap: Case 1 - Pile cap embedded into soil ($h = 0.175$ m); Case 2 - No contact of pile cap with soil ($h = 0$). Two different static loads ($W_s = 10$ kN and 12 kN including the weight of the pile cap and oscillator) were used in both the cases. For each static load, tests were conducted at four different eccentric moments ($W \cdot e = 0.187, 0.278, 0.366$, and 0.450 N m). Steady state dynamic response to harmonic excitation was measured under different frequencies for all eccentric moments at each static load.

TEST RESULTS

A set of response curves of vertical and coupled motion were plotted for different excitation levels. A typical frequency amplitude response curve of pile under vertical excitation is presented in Figure 3.

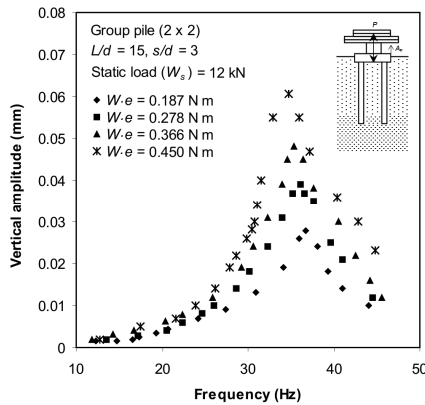


Fig. 3. Experimental frequency- amplitude response curves of pile for vertical vibration

The frequency versus amplitude response curves of pile group for both horizontal and rocking motion obtained from the coupled vibration test are presented in Figures 4 (a) and (b).

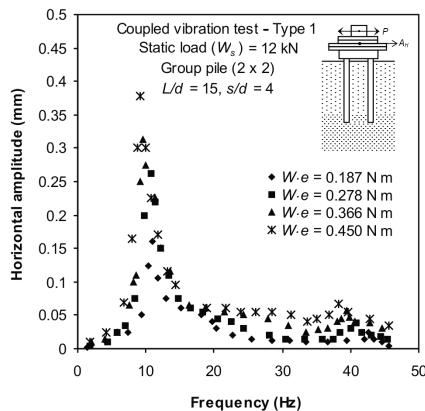


Fig. 4(a). Experimental frequency-horizontal amplitude response curves of pile for coupled vibration

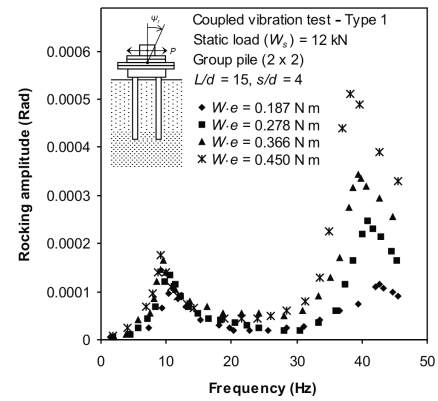


Fig. 4(b). Experimental frequency-rocking amplitude response curves of pile for coupled vibration

It can be seen from Figure 3 and 4 that the observed response curves display nonlinearity as the resonant frequencies decreases with increasing excitation intensity. The variations of natural frequency and resonant amplitude are observed for different s/d ratio of pile groups and it is found that the natural frequency increases and the resonant amplitude decreases with increasing pile spacing. It is observed that both the resonant frequency and resonant amplitude decreases as the static load increases. It is also found that the embedded pile cap (Case 1) produced higher resonant frequencies of pile than the no contact condition of pile cap (Case 2). However, the resonant amplitudes are higher for Case 2 as compared to Case 1.

THEORETICAL STUDY

In this study the continuum approaches by Novak and Aboul-Ella (1978) are used to analyses the dynamic behavior of single piles. In this approach, the stiffness and damping are calculated assuming that the soil is perfectly bonded to the pile. In nonlinear analysis for determining the impedance of single piles, the continuum approach is extended with a weak cylindrical boundary zone (Novak and Sheta, 1980) around the pile. To account approximately for the effect of slippage and nonlinearity it is assumed that an embedded cylindrical body is surrounded by a linear viscoelastic medium composed of two parts - an outer infinite region and an inner weak layer surrounding the cylindrical body as shown in Figure 5. Soil nonlinearity, as well as the weakened bond and slippage are presumed to be accounted for by a reduced soil shear modulus and increased soil damping of the inner soil layer. The soil reactions of such composite medium can be substituted into the theory described in linear analysis for calculation of stiffness and damping constants of piles embedded in layered media. The group stiffness and damping are calculated using the superposition method described in Novak and Mitwally (1990). With the stiffness and damping of single and group pile, the frequency-amplitude response curves of piles for different mode of vibration can be calculated using the computer program DYNA 5 (Novak *et al.*, 1999).

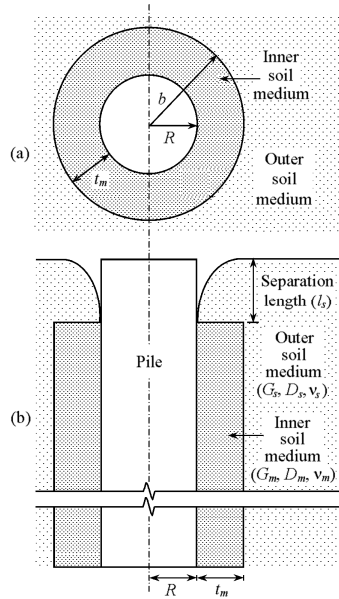


Fig. 5. Schematic presentation of nonlinear model
(a) Section view (b) Plan view

THEORY VERSUS EXPERIMENT

The soil parameter in the weakened zone and different pile separation length are adjusted so that the theoretical response curves approach the observed results. For vertical vibration, the variations of boundary zone parameters with depth for different excitation level are shown in Figure 6.

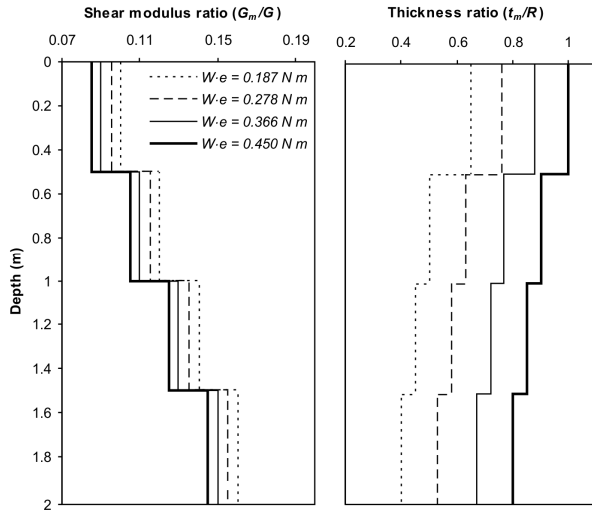


Fig. 6. Variations of boundary zone parameters with depth for vertical vibration

A typical comparison of experimental response curves and the theoretical predictions under vertical vibration is presented in Figure 7.

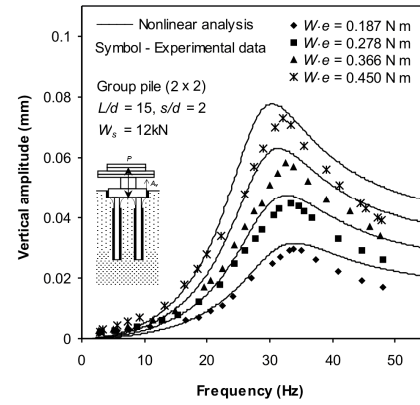


Fig. 7. Comparison of experimental results with that obtained by nonlinear analysis for vertical vibration

The comparisons between the theoretical and experimental results of group piles ($L/d = 15$, $s/d = 2$, $W_s = 10$ kN) are presented in Table 1 for coupled vibration.

Table 1. Comparison of experimental and theoretical results of group piles for coupled vibration

$W_s = 10$ kN, Case 2 – No contact of pile cap with soil						
Eccentric moment (N m)	Group pile ($L/d = 15$, $s/d = 2$)					
	f_{n1} (Hz)	A_{H1-res} (mm)	ψ_{r1-res} (Rad)	f_{n2} (Hz)	A_{H2-res} (mm)	ψ_{r2-res} (Rad)
Experimental results						
0.187	7.15	0.166	0.000119	38.96	0.015	0.000135
0.278	6.80	0.264	0.000203	36.86	0.025	0.000226
0.366	6.61	0.372	0.000264	36.53	0.034	0.000283
0.450	6.33	0.460	0.000315	34.05	0.046	0.000365
Theoretical results						
0.187	7.32	0.1784	0.000136	40.74	0.0191	0.000117
0.278	6.84	0.2715	0.000197	38.51	0.0273	0.000185
0.366	6.52	0.3645	0.000254	36.92	0.0371	0.000248
0.450	6.20	0.4549	0.000306	35.17	0.0451	0.000308

f_{n1} , f_{n2} = first and second resonant frequencies, A_{H1-res} , A_{H2-res} = first and second resonant amplitudes for horizontal motion, ψ_{r1-res} , ψ_{r2-res} = first and second resonant amplitudes for rocking motion

It can be seen from Figure 7 and Table 1 that very close agreement (for both resonant frequencies and amplitudes) between the theoretical prediction with observed results can be achieved by introducing the weak cylindrical zone around the pile and by providing sufficient pile separation with soil for both vertical and coupled motion.

SEPARATION BETWEEN PILE AND SOIL

An attempt is made to predict the length of separation of pile with the soil from the experimental results. It is a difficult task to measure the separation between the pile and soil at the time of testing for such small amplitude of vibration. A trial and error technique was therefore adopted. Different separation

lengths were chosen for each exciting intensity until the optimum match between the observed and theoretical results were achieved.

In order to combine the effect of static loads and embedment conditions of pile cap on separation length, two sets of plot of maximum vibration amplitude versus separation length are generated - one set for embedded pile cap conditions; and another set for no contact conditions of pile cap for both static loads ($W_s = 10$ kN and 12 kN). Best fit curves are drawn through the actual data points of each set for both embedded and no contact condition of pile cap as shown in Figure 8.

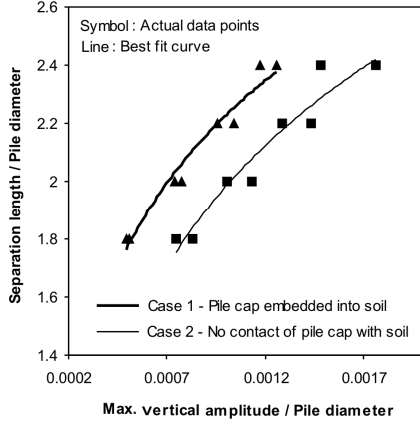


Fig. 8. Theoretical pile separation versus maximum amplitude of vertical vibration

The best fit curves through the data associated with the present soil conditions, the best fit curves can be mathematically expressed as follows:

(i) Pile cap embedded into soil (Case 1),

$$\frac{l_s}{d} = 0.6549 \ln\left(\frac{\Delta_v}{d}\right) + 6.7523 \quad (2)$$

(ii) No contact of pile cap with soil (Case 2),

$$\frac{l_s}{d} = 0.7743 \ln\left(\frac{\Delta_v}{d}\right) + 7.3311 \quad (3)$$

where l_s is the separation length between the pile and soil, Δ_v is the maximum vibration amplitudes of pile, and d is the pile diameter.

To establish the pile separation length, maximum vibration amplitude versus separation length is plotted for both horizontal and rocking mode of vibration. The maximum horizontal amplitude is considered for first-mode of vibration as the first resonant amplitudes is dominated by horizontal vibration. For rocking, the maximum amplitudes are considered for second-mode of vibration as the second peak is dominated by rocking vibration. Best fit curves are drawn

through the data points of each set for both horizontal and rocking mode of vibration. The pile separation lengths versus maximum amplitude curve for horizontal and rocking motions are shown in Figures 9 (a) and (b), respectively, for coupled vibration.

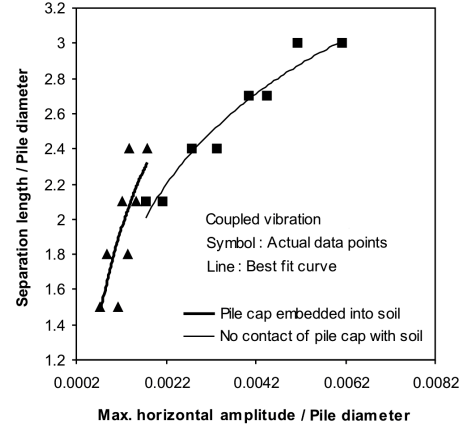


Fig. 9(a). Theoretical pile separation versus maximum horizontal amplitude of coupled vibration

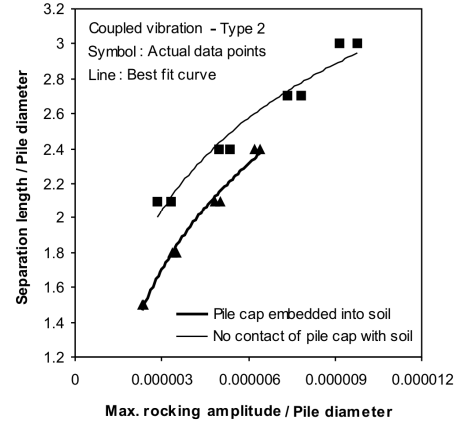


Fig. 9(b). Theoretical pile separation versus maximum rocking amplitude of coupled vibration

The best fitting curves through the data for coupled vibration can be mathematically expressed as follows:

(i) Pile cap embedded into soil (Case 1),

$$\frac{l_s}{d} = 0.969 \ln\left(\frac{\Delta_h}{d}\right) + 8.4596 \quad (4)$$

$$\frac{l_s}{d} = 0.8857 \ln\left(\frac{\Delta_r}{d}\right) + 12.964 \quad (5)$$

(ii) No contact of pile cap with soil (Case 2),

$$\frac{l_s}{d} = 0.7982 \ln \left(\frac{\Delta_h}{d} \right) + 7.0796 \quad (6)$$

$$\frac{l_s}{d} = 0.7636 \ln \left(\frac{\Delta_r}{d} \right) + 11.756 \quad (7)$$

where Δ_h is the maximum amplitude of pile for horizontal vibration, Δ_r is the maximum amplitudes of pile for rocking vibration in radian, and d is the pile diameter in millimetre. The above relationships are developed based on present soil-pile conditions and the characteristics of boundary-zone parameters.

CONCLUSIONS

This study describes field tests conducted on small prototype single and group piles under vertical and coupled vibration. A large number of dynamic tests with different exciting intensities are considered to study the frequency amplitude behaviour of piles. The observed response of piles under coupled vibration exhibit typical nonlinear behavior. Many parameters, namely, exciting intensities, static load, embedment of pile cap and s/d ratios have an influence on the nonlinear dynamic response of pile foundation.

The measured response curves of piles have been compared with the nonlinear analysis using the continuum approach of Novak. It has been found that the predicted values of resonant frequencies and amplitudes are close to the experimental results. The accuracy of the nonlinear theory in predicting the nonlinear response depends on the choice of boundary zone parameters and the length of pile separation.

It has been found that the separation length between pile and soil depends on excitation intensity. The length of separation of pile with soil is found different for vertical and coupled vibration. Some empirical relationships have been provided in this study for preliminary assessment of the separation between pile and soil as a function of maximum vibration amplitude for both vertical and coupled vibration.

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